

Reprinted from

Biophysical Chemistry

Biophysical Chemistry 91 (2001) 219–229

Electrostatic effects on the free-energy balance in
folding a ribosome-inactivating protein

Mark A. Olson*

Department of Cell Biology and Biochemistry, USAMRIID, 1425 Porter Street, Frederick, MD 21702, USA

Received 9 February 2001; received in revised form 30 April 2001; accepted 30 April 2001

20011003 102



BIOPHYSICAL CHEMISTRY

An International Journal devoted to the Physics and Chemistry of Biological Phenomena

Aims and Scope of the Journal

The journal is devoted to the interpretation of biological phenomena in terms of the principles and methods of physics and chemistry. It is receptive to articles which deal with biological molecules and systems, and to papers which treat systems serving as models for these. Treatments, phenomenological as well as molecular, of the interactions, structure and biological functions of individual biological macro-molecules and of supramolecular structures are also within the journal's domain.

EDITORS

A. COOPER (Principal Editor)

Department of Chemistry
Joseph Black Building
University of Glasgow
G12 8QQ, Scotland, U.K.
(Fax: 44-141-330-2910)
(E-mail: alanc@chem.gla.ac.uk)

C. BLOMBERG

Department of Theoretical Physics
Royal Institute of Technology
S-100 44 Stockholm, Sweden
(Fax: 46-8-104879)

I. HATTA

Department of Applied Physics
School of Engineering
Nagoya University
Nagoya 464-01, Japan
(Fax: 81-52-789-3724)
(E-mail: hatta@nuap.nagoya-u.ac.jp)

Founding Honorary Editor

M. MANDEL (Leiden, The Netherlands)

E. DI CERA

Department of Biochemistry and
Molecular Biophysics
Washington University School of Medicine
Box 8231
St. Louis, MO 63110, U.S.A.
(Fax: 1-314-3627183)
(E-mail: enrico@caesar.wustl.edu)

ADVISORY EDITORIAL BOARD

E. BUCCI, Baltimore, MD (USA)

O. BYRON, Glasgow (U.K.)
S.R. CAPLAN, Rehovot (Israel)
D.J. CARUANA, London (U.K.)
K.A. DILL, San Francisco, CA (USA)
D.T.F. DRYDEN, Edinburgh (U.K.)
M. EIGEN, Göttingen (Germany)
H. EISENBERG, Rehovot (Israel)
N. GO, Kyoto (Japan)
A. GOLDBETER, Brussels (Belgium)
A. GRÄSLUND, Stockholm (Sweden)
C.W. HILBERS, Nijmegen (The Netherlands)
H.-J. HINZ, Münster (Germany)
C. HO, Pittsburgh, PA (U.S.A.)
T. KAWAKUBO, Yokohama (Japan)
G. LÖBER, Jena (Germany)

E. MELO, Oeiras (Portugal)

O.G. MOURITSEN, Lyngby (Denmark)
E. NEUMANN, Bielefeld (Germany)
W.K. OLSON, Piscataway, NJ (U.S.A.)
P.L. PRIVALOV, Baltimore, MD (U.S.A.)
F.W. SCHNEIDER, Würzburg (Germany)
G. SCHWARZ, Basel (Switzerland)
J. SEELIG, Basel (Switzerland)
R.F. STEINER, Baltimore, MD (U.S.A.)
A.J.W.G. VISSER, Wageningen (The Netherlands)
A. WADA, Tokyo (Japan)
A. WATTS, Oxford (U.K.)
G. WEILL, Strasbourg (France)
K. WÜTHRICH, Zürich (Switzerland)
G. ZACCAI, Grenoble (France)
B.H. ZIMM, La Jolla, CA (U.S.A.)

Biophysical Chemistry (ISSN: 0301-4622) is published semimonthly except in July, October and December when it is published monthly. For 2001, 5 volumes, volumes 90-94, are scheduled for publication. Subscription prices are available upon request from the publisher. Subscriptions are accepted on a prepaid basis only and are entered on a calendar year basis. Issues are sent by surface mail except to the following countries where air delivery via SAL is ensured: Argentina, Australia, Brazil, Canada, Hong Kong, India, Israel, Japan, Malaysia, Mexico, New Zealand, Pakistan, PR China, Singapore, South Africa, South Korea, Taiwan, Thailand, USA. For all other countries airmail rates are available upon request. Claims for missing issues must be made within six months of our publication (mailing) date.

Orders, claims, and product enquiries: please contact the Customer Support Department at the Regional Sales Office nearest you:

New York: Elsevier Science, P.O. Box 945, New York, NY 10159-0945, USA; Tel. (+1)212-633-3730, [Toll free number for North American customers: 1-888-4ES-INFO (437-4636)], Fax (+1)212-633-3680, E-mail usinfo-f@elsevier.com

Amsterdam: Elsevier Science, P.O. Box 211, 1000 AE Amsterdam, The Netherlands; Tel. (+31)20-485-3757, Fax (+31)20-485-3432, E-mail nlinfo-f@elsevier.nl

Tokyo: Elsevier Science K.K., 9-15, Higashi-Azabu 1-chome, Minato-ku, Tokyo 106-0044, Japan; Tel. (+81)3-5561-5033, Fax (+81)3-5561-5047, E-mail info@elsevier.co.jp

Singapore: Elsevier Science, No. 1 Temasek Avenue, #17-01 Millenia Tower, Singapore 039192; Tel. (+65)434-3727, Fax (+65)337-2230, E-mail asiainfo@elsevier.com.sg

Rio de Janeiro: Elsevier Science, Rua Sete de Setembro 111/16 Andar, 20050-002 Centro, Rio de Janeiro-RJ, Brazil; Tel. (+55) (21) 509 5340; fax (+55) (21) 507 1991; e-mail: elsevier@campus.com.br [Note (Latin America): for orders, claims and help desk information, please contact the Regional Sales Office in New York as listed above]



ELSEVIER

Electrostatic effects on the free-energy balance in folding a ribosome-inactivating protein

Mark A. Olson*

Department of Cell Biology and Biochemistry, USAMRIID, 1425 Porter Street, Frederick, MD 21702, USA

Received 9 February 2001; received in revised form 30 April 2001; accepted 30 April 2001

Abstract

Electrostatics of globular proteins provides structural integrity as well as specificity of biological function. This dual role is particularly striking for ricin A-chain (RTA), an *N*-glycosidase which hydrolyzes a single adenine base from a conserved region of rRNA. The reported X-ray crystallographic structure of the RTA mutant E177A demonstrated a remarkable rescue of charge balance in the active site, achieved by the rotation of a second glutamic acid (Glu-208) into the vacated space. To understand this conformational reorganization, molecular-dynamics simulations were applied to estimate relative free energies that govern the thermodynamic stability of E177A together with mutants E177Q and E177D. The simulations anticipate that while E177A is a non-conservative substitution, the protein is more stable than the other two mutants. However, the structural plasticity of the RTA active site is not obtained penalty-free, rather E177A among the mutants shows the largest unfavorable net change in the electrostatic contribution to folding. Of the E177A folded state, reorganization of Glu-208 lowers the electrostatic cost of the free-energy change, yet interestingly, protein interactions oppose the rotational shift, while solvent effects favor the transition. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Ricin A-chain; Thermodynamic integration; Molecular dynamics; Hydration

1. Introduction

Knowledge of the determinants that govern thermodynamic stability of globular proteins is essential for understanding structure–function

correlates. For the large family of ribosome-inactivating proteins (RIPs), this includes factors that control the chain-folding process underlying translocation across cell membranes, as well as substrate recognition and binding to the ribosomal RNA. Upon cell uptake, RIPs function as *N*-glycosidases by removing an adenine base from 28S rRNA, consequently leading to inhibition of protein synthesis. Among the RIPs, ricin is the

* Tel.: +1-301-619-4236; fax: +1-301-619-2348.

E-mail address: molson@ncifcrf.gov (M.A. Olson).

most cytotoxic [1,2]. Ricin is a heterodimer consisting of a 267-residue catalytic A-chain (RTA) linked by a disulfide bond to a 262-residue B-chain, which mediates endocytosis by binding galactose residues present on various cell-surface glycoproteins and glycolipids.

The X-ray crystal structures of ricin [3–5] and several mutants of RTA [6–8] reveal that the active-site cleft is balanced by a network of negative and positive charges. The core of the RTA molecule is a long connecting α -helix, which exhibits a distinct bend near its C-terminal end, allowing charged residues Glu-177 and Arg-180 to form an ion-pair interaction at the molecular surface of the active site (see Fig. 1). Both residues are invariant in all known RIPs and are thought to play crucial roles in the catalytic mechanism [9]. For substrate recognition and binding, there are seven additional highly conserved polar residues located in the active site and four flanking solvent-exposed positively charged residues.

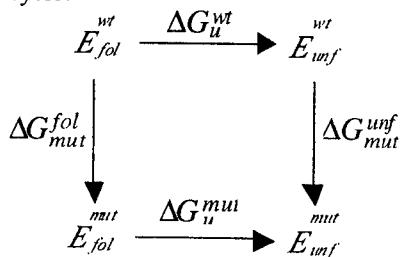
Substitutions that alter the active-site charge balance lead to structural rearrangements of the active site plus decreases in solubility as a function of pH as compared to wild-type (WT) RTA [8]. One of the more interesting structures arises from the conversion of Glu-177 to alanine (E177A) [7]. This mutant shows a second glutamic acid proximal to Glu-177 rotated into the active site to replace the deleted side chain, thus presumably rescuing the charge balance of the WT structure. Catalytic activity is also remarkably rescued by the E177A mutant, showing an insignificant loss of 20-fold [10], whereas mutants E177D and E177Q exhibited activity losses of 80- and 180-fold, respectively [10,11]. Replacing Arg-180 with histidine affects the global stability of RTA if the imidazole ring is deprotonated [8].

It is well recognized that proteins in their native conformational state are in a delicate balance of protein and solvent forces which can be disrupted or stabilized by relatively small changes in the side chains of key amino acid residues. What is not clearly understood is how interactions among individual residues are integrated in providing structural ‘plasticity’. To learn more about the factors that influence the stability of the RTA

active site, molecular-dynamics (MD) simulations were carried out of the folded and unfolded (denatured) structures of three RTA mutants derived from Glu-177. Free-energy simulation methods using a finite-difference thermodynamic integration technique (reviewed by Kollman [12]) were applied to estimating the relative folding stability of mutants E177Q, E177D and E177A. Simulations of the folded states were initiated from the WT crystal structure and the unfolded states from an extended chain conformation. Free-energy differences were decomposed into contributions arising from protein and solvent interactions. Although free energies of denaturation have yet to be determined for RTA and the mutants, simulations presented here provide new insights into the electrostatics among active-site residues and water molecules. This is particularly important for predicting how a protein thought a priori to be both non-functional and less stable can rescue activity, as illustrated by the mutation E177A. A practical implication of establishing a predictive scheme for estimating the effects of structural reorganization is the structure-based design of protein mutations with modified rRNA binding specificity. The reported calculations extend previous theoretical studies of RTA bound with a 29-mer RNA hairpin and substrate analogues [13–15], which demonstrated binding determinants of significant electrostatic contacts, several of which mimic protein and solvent interactions predicted in stabilizing the native conformation.

2. Theory and computations

Free-energy differences for the folded and unfolded state of the enzyme (denoted as E) were calculated based on the following thermodynamic cycle:



where ΔG_u^{wt} and ΔG_u^{mut} are the free energies of denaturation for the WT and mutant, respectively, and $\Delta G_{\text{mut}}^{\text{unf}}$ and $\Delta G_{\text{mut}}^{\text{fol}}$ are free energies for the unfolded and folded state, respectively, computed via simulation in which Glu-177 is converted to a substituting residue (Fig. 1). Substitutions studied include Glu \rightarrow Gln, Asp and Asp \rightarrow X and X \rightarrow Ala, where X denotes an intermediate residue designed to eliminate the negative charge of Asp by replacing the carboxylate group with an aldehyde moiety. This latter residue retains both side-chain volume and hydrogen-bonding potential, and when combined with the other substitutions, permits a systematic determination of the structural conditions that allow charge-balance reorganization to take place in the active site.

The relative free-energy change is obtained from the following:

$$\Delta\Delta G = \Delta G_u^{\text{mut}} - \Delta G_u^{\text{wt}} = \Delta G_{\text{mut}}^{\text{unf}} - \Delta G_{\text{mut}}^{\text{fol}}. \quad (1)$$

The computational method employed in evaluating Eq. (1) is based on a finite-difference thermodynamic integration algorithm [12,16] in which the respective free-energy differences for the folded and unfolded state are calculated by using the following master equation

$$\Delta G = \int_0^1 \frac{\delta G(\lambda)}{\delta \lambda} d\lambda = \int_0^1 \left\langle \frac{\delta H(\lambda)}{\delta \lambda} \right\rangle_\lambda d\lambda, \quad (2)$$

where the coupling parameter, λ , spans the interval from 0 (representing the WT state) to 1 (rep-

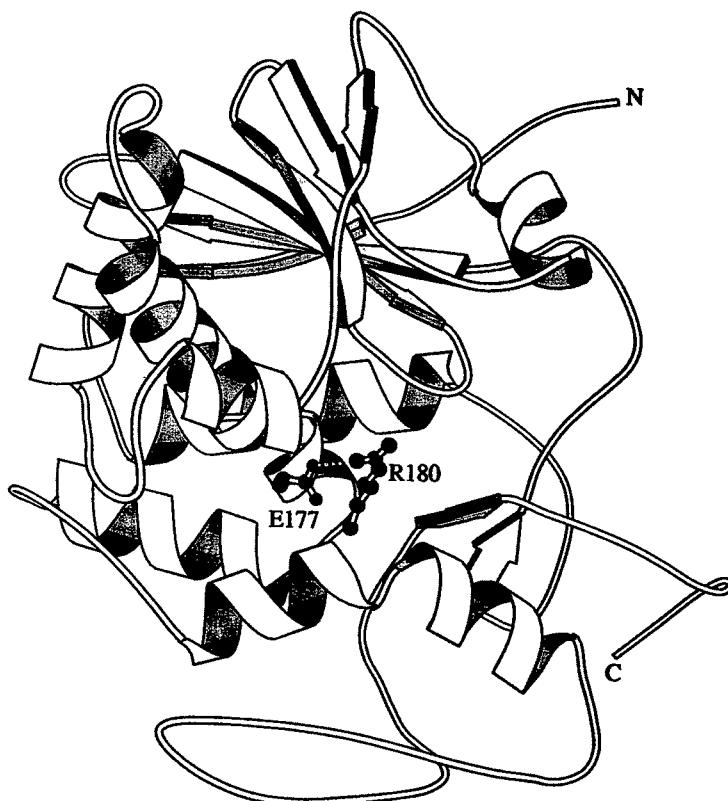


Fig. 1. Schematic illustration of a ricin A-chain Protein, highlighting the ion-pair interaction between residues Glu-177 and Arg-180. Figure produced using the MOLSCRIPT program [33].

resenting the mutant), and $\langle \rangle$ denotes an ensemble average over a Boltzmann sample of configurations governed by the Hamiltonian $H(\lambda)$. The kinetic component is generally not included in the free energy and the potential energy function $U(\lambda)$ is sampled. A statistical mechanical perturbation theory [17] can be used to compute $\delta G(\lambda)/\delta\lambda$ numerically by calculating the difference in free energy ΔG_i for a perturbation $\delta\lambda$ away from λ_i

$$\Delta G_i = -\frac{1}{\beta} \ln \langle e^{-\beta[U(\lambda_i \pm \delta\lambda) - U(\lambda_i)]} \rangle_{\lambda_i} \quad (3)$$

where $\beta = 1/k_B T$ (Boltzmann constant times absolute temperature). Calculations of Eq. (3) included both forward ($+\delta\lambda$) and backward ($-\delta\lambda$) perturbations with numerical integration of Eq. (2) carried out via a Gaussian-Legendre quadrature [18].

MD simulations were carried out for each λ point with trajectories generated for an active region composed of part of the enzyme inside a 12-Å spherical boundary centered on the initial position of C β of Glu-177 as derived from the X-ray crystal structure of the WT (PDB 1RTC). The unfolded state was represented as an extended conformation. Protein interaction potentials were modeled using the following form of the consistent valance force field [19]

$$\begin{aligned} U(\mathbf{R}) = & \sum_{\text{bonds}} K_b (b - b_0)^2 + \sum_{\text{angles}} K_a (\theta - \theta_0)^2 \\ & + \sum_{\text{dihedrals}} \frac{K_d}{2} [1 + \cos(n\varphi - \gamma)] \\ & + \sum_{i < j} \left[\frac{A_{ij}}{r_{ij}^{12}} - \frac{B_{ij}}{r_{ij}^6} \right] + \sum_{i < j} \frac{q_i q_j}{\epsilon r_{ij}} \\ & + \frac{1}{2} \sum_{i \in R} K_i \Delta r_i^2, \end{aligned} \quad (4)$$

where \mathbf{R} denotes the set of all atomic coordinates specifying the system conformation, b_0 and θ_0 are the equilibrium bond length and angle parameters, respectively; K_b and K_a are the bond and bond-angle stretching constants, respectively; K_d is the torsional force constant; n is the periodicity

of the torsional term, φ , and γ the phase angle; A_{ij} and B_{ij} are constants depending on the types of atoms i and j ; r_{ij} is the distance separating atoms i and j , q_i (q_j) is the partial charge of atom i (j), ϵ is the effective dielectric constant; and K_i is the harmonic restoring force constant acting on atom i displaced Δr_i in boundary region R . Parameterization of Eq. (4) as a function of λ was implemented at the level of the force-field parameters; e.g. the first term is given by

$$\begin{aligned} U_{\text{bond}}(b; \lambda) = & [\lambda K_b(\lambda_B) + (1 - \lambda) K_b(\lambda_A)] \\ & \times \{b - [\lambda b_0(\lambda_B) \\ & + (1 - \lambda) b_0(\lambda_A)]\}^2 \end{aligned} \quad (5)$$

where λ_A and λ_B refers to the WT and mutant state, respectively.

Active regions were immersed in an 8–10 Å deformable layer of solvent water. Water was represented by the SPC force-field potential [20]. Ionization states for residues Asp, Glu, Lys, Arg and His correspond to a neutral pH. The active regions consisted of 64 residues (1063 protein atoms) and 370 water molecules for the folded structure, and eight residues (126 protein atoms) and 524 water molecules for the extended structure. Boundary regions contained 203 residues and seven residues for the folded and extended structures, respectively. Amino acid residues lying in unsolvated outer shells were kept harmonically restrained at their initial positions by employing a force constant corresponding to a positional mean-square fluctuation of 0.52 Å², determined via an average over all protein atoms in a full 0.5-ns MD simulation of the WT structure. Biasing the search of phase space was necessary, particularly for the unfolded form, where without restraints the volume of accessible microstates reflected highly flexible peptides, rather than a denatured protein structure.

The simulation protocol consisted of all systems simulated at 10 values of λ connecting the initial state to the mutated state. The λ_1 simulations were initiated with 400 cycles of minimization using the steepest descent algorithm plus 1000 cycles of minimization via a conjugate gradient algorithm followed by a 10-ps equilibration

phase. The initial atomic velocities were assigned from a Gaussian distribution corresponding to a temperature of 300 K. Simulations for λ_2 , $\lambda_3, \dots, \lambda_{10}$ were carried out after a 10-ps equilibration started from the final step of the previous simulation. Ensemble averages were determined from simulations of 60 ps per λ value with non-bonded interactions smoothed to zero beyond 11.0 Å and a constant dielectric constant ($\epsilon = 1$) was used. End-point structures of the mutants ($\lambda = 1$) were determined following the λ_{10} simulation by averaging the trajectories of an additional 100-ps simulation. Integration of the equations of motion was performed using a 1.0-fs timestep.

3. Results and discussion

The free-energy simulation results for substitutions $\text{Glu-177} \rightarrow \text{Gln}$, Asp , and $\text{Asp} \rightarrow \text{X}$ and $\text{X} \rightarrow \text{Ala}$ are presented in Table 1. Supplementing the calculations of ΔG are free-energy decompositions at the protein (ΔG_{pro}) and solvent (ΔG_{sol}) level, with further decompositions at the force-

field level. Since we are primarily interested in electrostatic interactions of the active site, van der Waals and covalent interactions are combined into a single non-electrostatic component. Decompositions derived directly from force-field interactions must invoke the caveat that their free-energy contributions depend on the particular integration path (see Boresch et al. [21] and references cited therein), as well as the choice of force field. By contrast, the overall free-energy difference between two end states is independent of the path connecting them. All decompositions are consistent with Eq. (2), with the gradient of the potential evaluated via a second-order finite-difference scheme.

The simulations show the mutants E177Q, E177D and E177A are destabilized by 2.0, 1.2 and 1.1 kcal/mol, respectively. Free-energy differences for E177A were calculated from adding the contributions of E177D, D177X and X177A. As discussed below, each net change in stability is due to the partial cancellation of many terms, both positive and negative, some of which stabilize the WT structure and others the mutants. These

Table 1
Changes in free energies (kcal/mol) for ricin A-chain mutants

Mutation	Free energy contribution	$\Delta G_{\text{mut}}^{\text{unf}}$			$\Delta G_{\text{mut}}^{\text{fol}}$			$\Delta \Delta G$		
		tot	ele	non-ele	tot	ele	non-ele	tot	ele	non-ele
E177Q	Total	69.3	62.6	6.7	71.3	62.2	9.1	-2.0	0.4	-2.4
	Protein	-9.4	-18.8	9.5	47.9	35.8	12.1	-57.3	-54.6	-2.7
	Solvent	78.7	81.4	-2.7	23.4	26.4	-3.0	55.3	55.0	0.3
E177D	Total	10.6	42.4	-31.8	11.8	43.5	-31.7	-1.2	-1.1	-0.1
	Protein	-6.4	30.4	-36.8	-21.7	12.8	-34.5	15.3	17.6	-2.3
	Solvent	17.0	12.0	5.0	33.5	30.7	2.8	-16.5	-18.7	2.2
D177X	Total	100.3	102.2	-1.9	101.8	103.6	-1.8	-1.5	-1.4	-0.1
	Protein	13.7	16.6	-2.9	74.7	76.4	-1.7	-61.0	-59.8	-1.2
	Solvent	86.6	85.6	1.0	27.1	27.2	-0.1	59.5	58.4	1.1
X177A	Total	-13.9	-1.3	-12.6	-15.5	-2.1	-13.4	1.6	0.8	0.8
	Protein	-8.5	7.1	-15.6	-9.7	3.6	-13.3	1.2	3.5	-2.3
	Solvent	-5.4	-8.4	3.0	-5.8	-5.7	-0.1	0.4	-2.7	3.1
E177A	Total	97.0	143.3	-46.3	98.1	145.0	-46.9	-1.1	-1.7	0.6
	Protein	-1.2	54.1	-55.3	43.3	92.8	-49.5	-44.5	-38.7	-5.8
	Solvent	98.2	89.2	9.0	54.8	52.2	2.6	43.4	37.0	6.4

findings are in accordance with the work of others [22–26] and would seem to underscore the characterization suggested earlier by Karplus and co-workers [23], that essential elements of the thermodynamics that govern protein stability are ‘hidden’ in the net free-energy change, either measured or computed.

As with any application of free-energy simulation methods, there are various approximations underlying the simulation model that can introduce errors in the calculations [26–28]. These include approximations due to the force fields, truncation of long-range forces, sphere radius of the active-site region, and computational sampling of phase space. Additional approximation is that the unfolded state lacks any residual secondary structure, although several experimental and theoretical works may disfavor this assumption. Requisite testing of the cutoff distance and sphere size used in the models, as well as the length of 700 ps for the MD simulations, suggest that they were adequate. Systematic errors were estimated from analyzing the hysteresis derived via forward and backward perturbations, and showed values of approximately ± 0.6 kcal/mol for each net ΔG determination.

3.1. Mutation Glu-177 \rightarrow Gln

The individual free-energy changes from the amide substitution reflect predominately electrostatic components and show large unfavorable contributions, with values of 62.6 kcal/mol for the unfolded state and 62.2 kcal/mol for the folded state. The net effect on $\Delta\Delta G$ from electrostatic interactions is to marginally stabilize E177Q by 0.4 kcal/mol. Destabilization arises from non-electrostatic terms for a loss of –2.4 kcal/mol. Of the total $\Delta\Delta G$, electrostatic interactions from the protein are found to stabilize the unfolded chain conformation and destabilize the folded form, yielding a net decrease in stability of –54.6 kcal/mol. This loss is offset by a favorable electrostatic desolvation free energy of glutamine vs. glutamate, contributing 55.0 kcal/mol toward $\Delta\Delta G$.

The average MD simulation results for the active site of the WT structure and E177Q are

illustrated in Fig. 2a,b. Overall, the modeled WT structure is in good agreement with the crystallographic determination reported by Robertus and coworkers [3]. The carboxylate of Glu-177 is anchored in place by an ion-pair interaction between O ϵ 2 and Arg-180 NH₂, and a strong hydrogen bond between O ϵ 1 and the hydroxyl of Tyr-123. The charge neutralization arising from E177Q alters both interactions. Moreover, the perturbation leads to unfavorable changes in hydration surrounding the active site. Three hydrogen bonds with water are calculated for the WT Glu-177; O ϵ 1 bonds to two bridge forming waters, one forming a bridge to NH₂ of Arg-180 (similar to the water denoted as no. 334 of the crystal structure), and a second with O ϵ 2 of Glu-208; O ϵ 2 is hydrogen bonded to an additional third water. The simulation structure of E177Q shows one weak binding water molecule interacting with the side chain of Gln-177.

3.2. Mutation Glu-177 \rightarrow Asp

Eliminating one methylene group from the side chain of Glu-177 yields a mutant E177D that is less stable by 1.2 kcal/mol than the WT structure, but 0.8 kcal/mol more stable than E177Q. In contrast with E177Q, the net electrostatic effect of the mutation is to favor the unfolded state ($\Delta\Delta G = -1.1$ kcal/mol). A further difference with E177Q is that the net protein electrostatic contribution for E177D favors the mutant form, while solvent effects destabilize the substitution. Of the folded conformation, the electrostatic perturbation on protein interactions is much less than the amide conversion (~13 vs. 36 kcal/mol). Fig. 2c shows the carboxylate of Asp-177 preserving the ion-pair interaction with NH₂ of Arg-180, although at an energetic cost of shifting the positively charged residue. Similarly, a hydrogen bond is formed comparable to the WT structure with the hydroxyl of Tyr-123, yet requires a conformational displacement of ~1 Å. Because the substitution conserves the negative charge, the carboxylate of Glu-208 is predicted to occupy a position similar to that of the WT structure, maintaining the interaction with Gln-177.

The simulation structure of the active-site re-

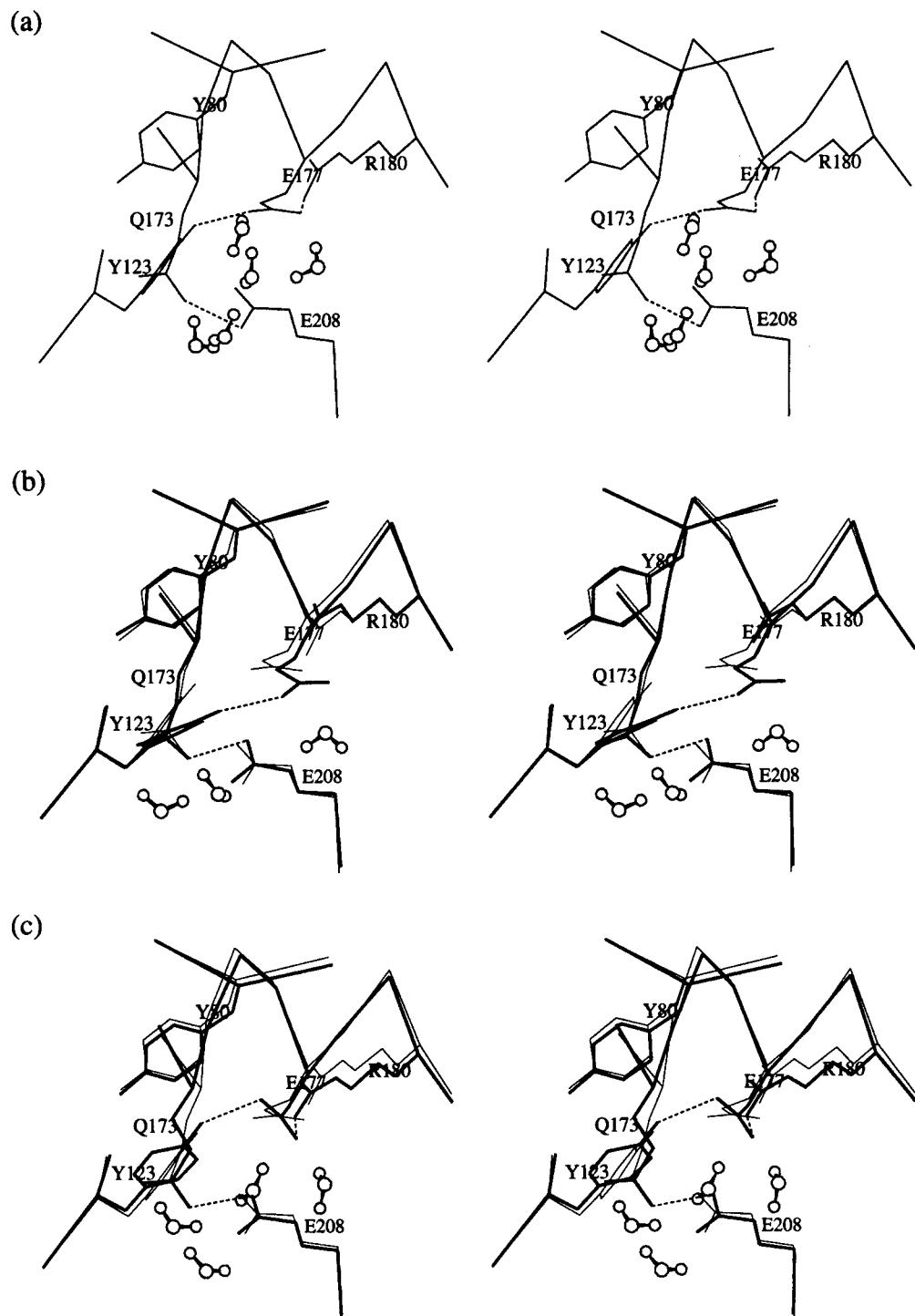


Fig. 2. Results of the molecular dynamics simulations of wild-type structure and amino acid substitutions at position 177 of the ricin A-chain protein in explicit solvent water. (a) The active site of the wild-type structure. Water molecules are illustrated as ball-and-stick models. Only the water interacting with side chains of Glu-177 and Glu-208 are shown. (b) Contrast between the calculated E177Q active site and the average simulation wild-type structure. The thick line denotes the mutant and thin line shows the wild-type protein. Waters correspond to the mutant structure. Simulation structures for (c) E177D and (d) E177A mutants.

(d)

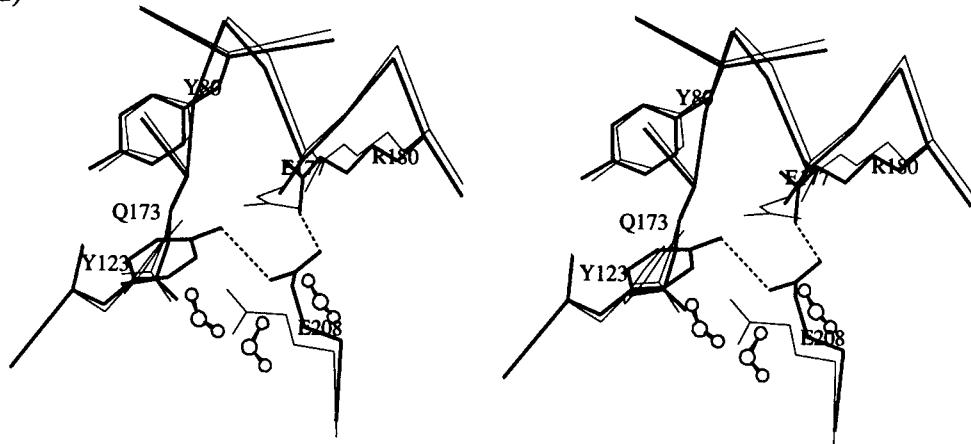


Fig. 2. (Continued).

gion indicates two waters are bound by Asp-177 and, because of the structural reorganization in residues Tyr-123 and Arg-180, the solvent contribution is less favorable than that calculated for E177Q. Nevertheless, the bound waters are more consistent with the WT structure and should contribute favorably to catalysis. For the unfolded state, displacement of the charge yields a more stable free energy of solvation than that corresponding to the charge deletion of E177Q.

3.3. Mutation Glu-177 → Ala

The free-energy perturbation of glutamate to alanine was expanded into three intermediate steps: E177D; D177X; and X177A. As mentioned above, X denotes a side chain in which the carboxylate of Asp has been replaced with an aldehyde group. The idea was to design a residue that eliminates the forking interactions of the carboxylate while retaining the potential for a single hydrogen bond. From Table 1, the conversion of Asp to X significantly disrupts the electrostatic stability ($\Delta\Delta G = -1.4$ kcal/mol) greater than either E177Q (+0.4 kcal/mol) or E177D (-1.1 kcal/mol). Protein contributions are unfavorable in both unfolded and folded conformations, leading to a net destabilization of -61.0 kcal/mol. The calculations for the folded form show that the decreased polarity for hydrogen bonding of X

contributes to an electrostatic free-energy loss of nearly 30 kcal/mol greater than the charge neutralization of E177Q, and approximately 60 kcal/mol for a comparison with E177D.

Structurally, the residue X-177 preserves the hydrogen bond with Arg-180 (data not shown), although much weaker than the WT ion pair. The substitution also disrupts the electrostatic attraction between X-177 and Tyr-123. For residue Glu-208, the calculated structure indicates a lack of significant dihedral angle perturbation. This implies that the reduced solvent-exposed polarity at position 177 while retaining side-chain volume is insufficient to allow the proximal glutamate to reorganize the charge balance of the active site. As for solvent effects, the net contribution of transferring the mutant from vacuum to solution is favorable (~60 kcal/mol) and is similar to E177Q (~55 kcal/mol).

The replacement of X with alanine is the final step in obtaining E177A and yields a protein X177A that shows an *increase* in thermodynamic stability by a $\Delta\Delta G$ of 1.6 kcal/mol. The significance of this result is that the improved stability is obtained by the dihedral rotation of Glu-208 to fill the active-site cavity. The recovery in stability yields the least unfavorable electrostatic component among the series of folded protein changes arising from the substitutions. Moreover, the modification displays favorable net protein and

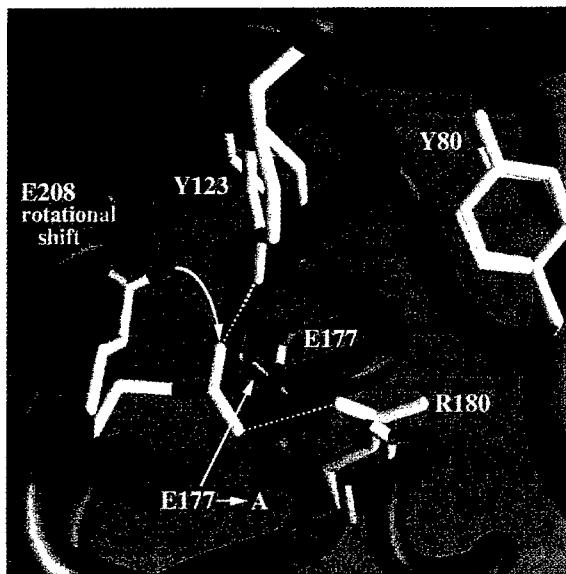


Fig. 3. Molecular modeling drawing of the reorganization calculated for the E177A structure and its comparison with the wild-type structure for ricin A-chain. The color yellow designates the side chains of E177A and the blue colored worm shows the backbone. Side chains of the wild-type structure are shown in white, with oxygen atoms illustrated in red and nitrogen atoms in blue. Figure produced using the GRASP program [34].

solvent contributions for both unfolded and folded conformations, however, the total electrostatic component from solvent interactions is unstable.

For E177A, individual contributions to $\Delta\Delta G$ are dominated by unfavorable electrostatic changes, yet interestingly, it is the non-electrostatic component that makes E177A more stable than either E177Q or E177D. The average simulation structure for the active site of mutant E177A is shown in Fig. 2d with a superposition of WT simulation structure and the two structures are contrasted schematically in Fig. 3. The structural difference is primarily the rotation of the carboxylate of Glu-208 in accordance with the X-ray crystal structure [7]. As expected, Ala-177 has no strongly interacting waters in the folded state and only one in the unfolded state through backbone interactions. Presumably, the functional hydration sites for catalysis are now provided by the side-chain reorganization in Glu-208.

From the average E177A simulation structure,

the side chain of Glu-208 has dihedral angles of $\chi_1 = -140.2^\circ$ and $\chi_2 = 62.5^\circ$, which correspond to a less-populated rotameric state [29]. Because of the rotation, the carboxylate of 208 breaks the WT interaction with Gln-173, yet gains two alternative hydrogen bonds within the protein active site. The first is with Tyr-123, which undergoes a rearrangement allowing the interaction to take place, and the second is with the guanidinium group of Arg-180, which appears to move upward in the active site. The X-ray crystal structure of the mutant E177A also shows Tyr-80 rotated outward toward the solvent [7], whereas the simulation of 700 ps places the residue in a similar conformation as found in the WT structure. Owing to this lack of significant movement in Tyr-80 in the simulation, it is anticipated that the calculated $\Delta\Delta G$ of -1.1 kcal/mol may approximate an upper bound in stability change for E177A.

To understand better the role of Glu-208 and its rotation into the active site, additional free-energy simulations of $X177 \rightarrow A$ were performed where the glutamate side chain was restricted to its WT configuration. The motivation for these calculations was a crystallographic analysis of the E177A structure, which showed that approximately 15% of the molecules retained the non-rotated configuration for Glu-208 [7]. Using occupancy populations of 85 and 15%, a free-energy difference between the two Glu-208 configurations is estimated at ~ -1 kcal/mol, favoring side-chain rotation. From the observation that the side-chain rotation of Glu-208 occurs during the $X \rightarrow A$ substitution, the simulation model for this perturbation provides a reasonable approach for calculating the conformational free-energy difference. Simulation results for the reorganization are presented in Table 2. Because of energy conservation problems with the WT configuration, thermal initialization was extended for both states to 75–80 ps per λ point starting with the λ_7 perturbation.

The results show that the side-chain reorganization in Glu-208 is favored thermodynamically by a ΔG of -1.4 kcal/mol. Without forcing the rotation in Tyr-80, the calculated ΔG is in excellent agreement with the crystallographic estimate. The calculations further show that the elec-

Table 2
Conformational reorganization free energy (kcal/mol) for residue Glu-208 in the structure E177A

Free energy contribution	ΔG			
	exp ^a	tot	ele	non-ele
Total	−1.0	−1.4	−0.5	−0.9
Protein	−	6.9	7.0	−0.1
Solvent	−	−8.3	−7.5	−0.8

^a Experimental estimate taken from Kim et al. (1992).

trostatic component shifts the equilibrium between the two conformers toward structural reorganization. Moreover, and perhaps unexpected, the results indicate that relative to the WT configuration the protein interactions of the active site oppose the rotation of Glu-208. Despite the favorable pair-wise interactions of Glu-208 with side chains of Arg-180 and Tyr-123, electrostatic clashes with the residual protein backbone make ΔG_{pro} less than optimal. This is not to say that the reorganized protein free-energy surface is unfavorable, but rather the more populated E177A active-site configuration contains electrostatic strain. Conversely, solvent interaction promotes the conformational reorganization. The folding of E177A retains greater solvent accessibility for the side chain of Glu-208 than the WT configuration, and thus yields a lower desolvation cost reflected in the calculated electrostatic component of ΔG_{sol} . A similar argument can be suggested for Tyr-80 in the crystal structure, where side-chain rotation is favored due to solvent interactions.

From the model calculations, a general picture of the thermodynamic stability of the RTA active site emerges. While the electrostatic cost of desolvation due to the release of water from the protein active-site surface upon folding favors charge deletion of Glu-177, maintaining ion-pair complementarity is a necessary component for minimizing the thermodynamic loss in stability. This is evident from eliminating the negative charge at position 177 without allowing significant electrostatic reorganization (illustrated by mutants E177X or the WT configuration of E177A,

both showing a value for $\Delta \Delta G \leq -2.5$ kcal/mol). Overall, structural plasticity arises from searching the free-energy surface for the configuration that yields the minimum reorganization penalty. Protein reorganization of RTA from charge deletions is unfavorable in terms of electrostatics, while solvent reorganization shifts the populations on the energy landscape in a fashion that recovers a significant fraction of the loss in conformational stability. Although still debated is the issue of whether hydrogen bonds make stabilizing contributions to the free-energy difference between the unfolded and folded state [30–32], it is clear that charge balance is a critical element of optimizing the self-organization of the native tertiary fold.

The calculations presented here demonstrate that free-energy simulation methods are capable of detecting a remarkable reorganization of the RTA active site subjected to the non-conservative perturbation of E177 → A. The E177A crystal structure emphasizes the importance of considering structural plasticity in interpreting mutagenic results. A promising aspect of the calculations is a modeling approach for understanding the underlying forces that stabilize RTA and its mutants. Moreover, the calculations provide a strategy for anticipating the effects of additional substitutions aimed at eliminating the cytotoxicity of ricin, while preserving antigenic determinants characteristic of the WT protein.

Acknowledgements

This work was supported by a generous grant of computer time from the Advanced Biomedical Computing Center of the Frederick Cancer Research and Development Center, National Cancer Institute.

References

- [1] K. Eiklid, S. Olsnes, A. Pihl, *Expt. Cell Res.* 126 (1980) 321.
- [2] S. Olsnes, A. Pihl, in: P. Cohen, S. van Heyningen (Eds.), *Molecular Action of Toxins and Viruses*, Elsevier Biomedical Press, New York, 1982, p. 52.

- [3] B.J. Katzin, E.J. Collins, J.D. Robertus, *Proteins* 10 (1991) 251.
- [4] E. Rutenber, B.J. Katzin, E.J. Collins et al., *Proteins* 10 (1991) 240.
- [5] S.A. Weston, A.D. Tucker, D.R. Thatcher, D.J. Derbyshire, R.A. Pauplit, *J. Mol. Biol.* 244 (1994) 410.
- [6] Y. Kim, J.D. Robertus, *Protein Eng.* 5 (1992) 775.
- [7] Y. Kim, Y.D. Mlsna, A.F. Monzingo, M.P. Ready, A. Frankel, J.D. Robertus, *Biochemistry* 31 (1992) 3294.
- [8] P.J. Day, S.R. Ernst, A.E. Frankel et al., *Biochemistry* 35 (1996) 11098.
- [9] A.F. Monzingo, J.D. Robertus, *J. Mol. Biol.* 227 (1992) 1136.
- [10] D. Schlossman, D. Withers, P. Welsh, A. Alexander, J.D. Robertus, A. Frankel, *Mol. Cell Biol.* 9 (1989) 5012.
- [11] M.P. Ready, Y.S. Kim, J.D. Robertus, *Proteins* 10 (1991) 270.
- [12] P. Kollman, *Chem. Rev.* 93 (1993) 2395.
- [13] M.A. Olson, J.P. Scovill, D.C. Hack, *J. Comput. Aided Mol. Des.* 9 (1995) 226.
- [14] M.A. Olson, *Proteins* 27 (1997) 80.
- [15] M.A. Olson, L. Cuff, *Biophys. J.* 76 (1999) 28.
- [16] W.F. van Gunsteren, in: W.F. van Gunsteren (Ed.), *Computer Simulations of Biomolecular Systems*, ESSCOM, Leiden, 1989, p. 27.
- [17] R.W. Zwanzig, *J. Chem. Phys.* 22 (1954) 1420.
- [18] W.H. Press, B.P. Flannery, S.A. Teukolsky, W.T. Vetterling, *Numerical Recipes in FORTRAN: The Art of Scientific Computing*, Cambridge University Press, Cambridge, 1986.
- [19] P. Dauber-Osguthorpe, V.A. Roberts, D.J. Osguthorpe, J. Wolff, M. Genest, T. Hagler, *Proteins* 4 (1988) 31.
- [20] H.J.C. Berendsen, J.P.M. Postma, W.F. van Gunsteren, J. Hermans, in: B. Pullman (Ed.), *Intermolecular Forces*, Dordrecht, Reidel, 1981, p. 331.
- [21] S. Boresch, G. Archontis, M. Karplus, *Proteins* 20 (1994) 25.
- [22] L.X. Dang, K.M. Mertz, P.A. Kollman, *J. Am. Chem. Soc.* 111 (1989) 8505.
- [23] J. Gao, K. Kuczera, B. Tidor, M. Karplus, *Science* 244 (1989) 1069.
- [24] B. Tidor, M. Karplus, *Biochemistry* 30 (1991) 3217.
- [25] T. Simonson, A.T. Brünger, *Biochemistry* 31 (1992) 8661.
- [26] L. Wang, D.L. Veenstra, R.J. Radmer, P.A. Kollman, *Proteins* 32 (1998) 438.
- [27] R.J. Radmer, P.A. Kollman, *J. Comput. Chem.* 18 (1997) 902.
- [28] A. Di Nola, A.T. Brünger, *J. Comput. Chem.* 19 (1998) 1229.
- [29] J.W. Ponder, F.M. Richards, *J. Mol. Biol.* 193 (1987) 775.
- [30] Z.S. Hendsch, B. Tidor, *Protein Sci.* 3 (1994) 211.
- [31] B. Honig, A.S. Yang, *Adv. Protein Chem.* 46 (1995) 27.
- [32] J.K. Myers, C.N. Pace, *Biophys. J.* 71 (1996) 2033.
- [33] P. Kraulis, *J. Appl. Cryst.* 24 (1991) 946.
- [34] A. Nicholls, K.A. Sharp, B. Honig, *Proteins* 11 (1991) 281.

INFORMATION TO AUTHORS

(The full Instructions To Authors can be found in *Biophysical Chemistry*, Vol 89, No. 1, pp. 101–104 and also on the World Wide Web: access under <http://www.elsevier.nl> or <http://www.elsevier.com>).

Biophysical Chemistry publishes original **research papers** covering the subjects outlined in the 'Aims and Scope of the Journal'. It also welcomes critical **review articles**, and suggestions of relevant topics offered to one of the Editors will be considered.

Research papers should be sent in triplicate to one of the Editors (addresses and Telefax numbers given on the inside front cover). Submission of a paper to *Biophysical Chemistry* is understood to imply that this is original and unpublished and has neither been published in part nor is being considered elsewhere, and that all authors agree to the submission. The names of at least three possible referees must be indicated in the submission letter. Wherever possible, a copy of the abstract should also be submitted by e-mail. Final versions of accepted manuscripts must be submitted to the handling Editor as hard copies in triplicate, together with a matching electronic file (Word or WP preferred) on disk.

Review articles: Critical reviews are published by invitation of the Editors, but may also be submitted. A modest fee will be paid to the senior author upon publication of the review. For more details please contact one of the Editors.

All manuscripts will be evaluated according to the peer refereeing system. They must be in English, and typed with double or triple spacing, first copies (or clear photocopies thereof) with a wide margin; all pages should be numbered. Before mailing the manuscripts, please check the following points:

Title: The title should be chosen for its information content such that it conveys to the informed reader the particular nature of the contents of the paper.

Keywords: Authors are requested to select a maximum of six keywords (or short phrases) and include them with the submitted typescript. These will be used in the compilation of the volume cumulative index and will be printed on the title page of the published article. (Authors should note that American spelling is used and that plural terms are avoided where possible.) Important factors of the investigation as a whole should be selected as keywords and general terms like, membrane, transport, etc., should be avoided. In some cases, the general term can be used when qualified, e.g., membrane protein, K^+ transport, etc. The keywords should be chosen so that the combination of these (as they will appear in the published index) will give the reader sufficient direct information as to the relevance of a given article to his/her particular field. Example: *Title:* Computer simulation of T3/T7 phage infection using lag times — *Keywords:* Infection mechanism; Protein synthesis; DNA replication; Lag time; Computer simulation; (Phage T3, Phage T7)

The submitted list may be amended by the editorial office to ensure that index entries are consistent throughout the cumulative index. If words appear in parentheses, this indicates that these words are appropriate to the article, but are not of sufficient indexing value; these words will not appear as individual index entries, but will be printed each time a keyword index entry appears.

Abstract: The abstract of 100–150 words should contain all the details of the methods and the results obtained, and be written in such a way that it will address a wider audience.

Address: The name(s) of the author(s) and the name and address of the institute(s) where the research work was done should be indicated on the manuscript.

Communication: The full postal address, fax and telephone numbers, and e-mail address of the corresponding author must be given on the first (title) page of the manuscript. Proofs will be sent to the e-mail address provided unless specified otherwise.

Figures: The drawings for the figures must be submitted on separate sheets, drawn in black Indian ink in large size and carefully lettered (with the use of stencils). The lettering as well as the details should have proportionate dimensions so as not to become illegible or unclear after the usual reduction by the printers; in general the figures should be designed for a reduction factor of two to three. Each figure should have a number and a caption; the captions should be collected on a separate sheet and typed with **double** or **triple** spacing. The appropriate place of a figure should be indicated in the margin. Your figure material will be returned after publication of the article if so desired. Colour figures can be published at the author's expense.

Formulae: Displayed formulae should be numbered and typed or clearly written by hand, with extra spacing allowed above and below. Vectors will be printed in bold-face italics (heavy, slanting type), and should be indicated by a wavy underlining in the typescript. Special attention should be paid to characters that can easily be misread, such as i (lower case), I (cap.), l (el), l (one), $\acute{}$ (prime), o (lower case), O (cap.), 0 (zero), \circ (degree), u , v (vee), ν (Greek nu), V (cap.), x , \times , X , z , Z , p , ρ (Greek rho), etc., and definition of such characters should be given in the margin.

Tables: Tables should be typed on separate sheets. Each table should have a number and a title. The appropriate places for the insertion of the tables should be indicated in the margin. Table legends should be typed with **double** or **triple** spacing.

References: In the text, reference to other parts of the paper should be made by section (or equation) number, not by page number. References to other papers should be consecutively numbered in the text and should be listed by number, as in the examples:

Book: R. Zallen, *The Physics of Amorphous Solids*, Wiley, New York, 1983.

Journal articles: T.P. Burghardt, J.E. Lyke and K. Ajtai, Fluorescence emission and anisotropy from rhodamine dimers, *Biophys. Chem.* 59 (1996) 119–131.

Paper in a contributed volume: E. Stelzer, H. Ruf, in G. Spach (Ed.), *Physical Chemistry of Transmembrane Motion (Studies in Physical and Theoretical Chemistry*, Vol. 24), Elsevier, Amsterdam, 1983, p. 37.

Unpublished paper: D. Schallreuther, Ph.D. thesis, Universität Konstanz (1982).

'Personal communication', 'in preparation', 'unpublished results', etc., should not be cited in the reference list but in the text.

Reprints: 50 free reprints per contribution will be made available. Further reprints may be ordered by filling in and returning to the publisher the order form sent to contributors.

Electronic manuscripts. Electronic manuscripts have the advantage that there is no need for the rekeying of text, thereby avoiding the possibility of introducing errors and resulting in reliable and fast delivery of proofs. For the initial submission of manuscripts for consideration, hardcopies are sufficient, but submitting as a PDF file to Dr Cooper or Dr Di Cera may considerably shorten the reviewing time. For the processing of **accepted papers**, electronic versions are preferred. After **final acceptance**, your disk plus three final and exactly matching printed versions should be submitted together. Double density (DD) or high density (HD) diskettes (3.5 or 5.25 inch) are acceptable. It is important that the file saved is in the native format of the wordprocessor program used. Label the disk with the name of the computer and word-processing package used, your name, and the name of the file on the disk. Further information may be obtained from the Publisher.

Authors in Japan please note: Upon request, Elsevier Science Japan will provide authors with a list of people who can check and improve the English of their paper (*before submission*). Please contact our Tokyo office: Elsevier Science K.K., 1-9-15 Higashi-Azabu, Minato-ku, Tokyo 106-0044; Tel. (03)-5561-5032; Fax (03)-5561-5045.

Biophysical Chemistry has no page charges

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 9/20/01	3. REPORT TYPE AND DATES COVERED
4. TITLE AND SUBTITLE Electrostatic effects on the free-energy balance in folding a ribosome-inactivating protein		5. FUNDING NUMBERS	
6. AUTHOR(S) Mark A. Olson			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Commander, U.S. Army Medical Research Institute of Infectious Diseases 1425 Porter Street Fort Detrick, MD 21702-5011		8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES			
12a. DISTRIBUTION / AVAILABILITY STATEMENT APPROVED FOR PUBLIC RELEASE DISTRIBUTION UNLIMITED		12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Electrostatics of globular proteins provides structural integrity as well as specificity of biological function. This dual role is particularly striking for ricin A-chain (RTA), an N-glycosidase which hydrolyzes a single adenine base from a conserved region of rRNA. The reported X-ray crystallographic structure of the RTA mutant E177A demonstrated a remarkable rescue of charge balance in the active site, achieved by the rotation of a second glutamic acid (Glu-208) into the vacated space. To understand this conformational reorganization, molecular-dynamics simulations were applied to estimate relative free energies that govern the thermodynamic stability of E177A together with mutants E177Q and E177D. The simulations anticipate that while E177A is a non-conservative substitution, the protein is more stable than the other two mutants. However, the structural plasticity of the RTA active site is not obtained penalty-free, rather E177A among the mutants shows the largest unfavorable net change in the electrostatic contribution to folding. Of the E177A folder state, reorganization of Glu-208 lowers the electrostatic cost of the free-energy change, yet interestingly, protein interactions oppose the rotational shift, while solvent effects favor the transition.			
14. SUBJECT TERMS Ricin A-chain; Thermodynamic integration; Molecular dynamics; Hydration		15. NUMBER OF PAGES 14	16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT